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Quasi-elastic scattering

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Abstract : Interesting features are observed in quasi-elastic reactions. The heavy-ion transfer reaction throws light on the underlying reaction mechanism.

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In the previous session, we have already sat through a talk on heavy-ion elastic scattering. It is my duty now to carry it on a little further. I begin by describing quasi-elastic scattering.

One of the advantages of the heavy-ion scattering in that the deBroglie wave length $\lambda = \hbar / \sqrt{2mE}$ is small. For on ^{58}Ni ion at an energy of 120 MeV, available at the NSC Pelletron, λ is 0.3 fm, which is much less than the size of the $^{58}\mathrm{Ni} = 1.4 \times 58^{1/3} = 4$ fm. Therefore classical picture is often adequate. We can define a trajectory of the scattered particle. We can also define an impact parameter b and a distance of closest approach d as shown in Figure 1. For large impact parameter, only coulomb interaction will be effective,

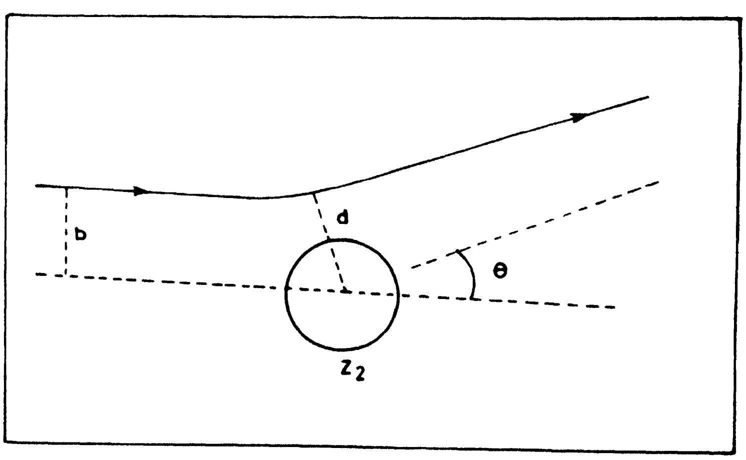

Figure 1. Trajectory of scattered particle.

and Rutherford scattering will take place. At some what smaller one, where the projectile grazes along the target, there will be contributions from nuclear interaction. As a result, besides elastic scattering, there will be inelastic and one, two or multi-nuclear transfer. Since the projectile and the ejectile will be only slightly different, the elastic, inelastic and the transfer reaction are together called quasi-elastic reaction. The coulomb trajectory is likely to be only very slightly altered. Another reason for lumping the inelastic and transfer reactions together is that for heavy-ion projectiles, the energy resolution of the scattered particle is low, mainly because of energy loss, straggling, kinematic broadening *etc* in the target. Consequently, discrete peaks are not observed, besides the elastic peak. All of the inelastic and transfer events can be together characterized by a quasi-elastic peak.

Quasi-elastic phenomena for heavy-ion projectile show certain characteristic features. Chief among these is l-space localization. The reflection co-efficient, which is a measure of the flux being thrown back in the entrance channel and therefore of elastic scattering, as a function of l can be represented as shown in Figure 2. Since $l = kb$, small l means small impact parameter and therefore a larger chance of the projectile hitting the

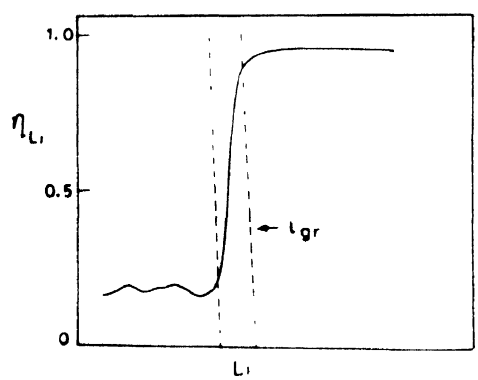

Figure 2. The reflection coefficient as a function of l

interior. Because of the presence of many reaction channels, low partial waves (l values) are going to be absorbed. For higher l-values there is complete reflection. The quasi-elastic cross section is thus going to be determined by l grazing, in between the completely absorbed partial waves and the completely reflected ones. Instead of a series of l-values only a few l values, around l grazing will contribute. A related matter is the optimum Q-value for the reactions. The cross section will be maximum when the ingoing trajectory for the projectile match the outgoing trajectory of the ejectile (which is certainly the case for elastic scattering). For n transfer, the Coulomb potential energy does not change, after transfer, so that the trajectories remain similar and optimum Q-value is zero (similar to elastic scattering). For p transfer, Coulomb potential energy go-down for stripping from the lighter projectile; so if Q value is –ve, total energy goes down, kinetic energy remains constant, keeping the trajectory to be the same. Usually, proton stripping in favoured, because –ve Q- values are more common for these reactions.

The purpose of this talk would be to concentrate on a few recent advances and interesting findings in the field of quasi elastic reactions. The first among these that I would touch upon is the so-called threshold anomaly. It was pointed out in around 1984-85, by Lilley *et al* [1] that the energy dependent part of the optical potential required to describe elastic scattering data around the Coulomb barrier, showed a certain behaviour. The imaginary part of the potential increased slowly around the barrier and eventually saturated to some constant value. The real part of the potential slowly rises and then falls gradually as the energy increases above the barrier. The behaviour of the absorptive potential is understandable, since as the energy increases more channels open up and flux is lost from the entrance channel. The behaviour of the real part is not so clear, until one realises, as was pointed by Nagarajan *et al* [2], that a dispersion relation connects the energy varying part of the real potential, to an energy integral of the imaginary part. This real potential is called polarization potential and indicates coupling to closed channels, where flux can only go through a virtual process. In the absorptive potential, on the contrary, one takes care of actual of flux the threshold anomaly has been measured for various target, projectile combination. It is really no anomaly in that sense, but it emphasizes the importance of channel coupling around the barrier. In that sense it is related to enhancement of sub barrier fusion, which has been known for a long time and is also believed to be due mainly to channel coupling.

The imaginary potential is a way of taking into account the coupling to other channels. The coupled equations can be cast in a way, so that the wave-function in one channel is coupled to wave function in another channel through a non-diagonal term.

The diagonal term is the elastic scattering potential for the given channel. The threshold anomaly is exhibited by this term. It was arged by Satchler [3], that the non-diagonal terms should similarly show energy-dependent behaviour. A consequence of this is that for 0^+–2^+ inelastic scattering, the excitation function (cross section as a function of energy) may show anamalous behaviour, near the Coulomb barrier. One of the coupling terms for deformed nuclei is the re-orientation term. Indeed, it was seen in ^{16}O + ^{92}Zr scattering [4] (θ_{CM} = 174°) that the prediction from theory did not fit the Coulomb-nuclear interference minimum and rather unusually large values of re-orientation term was needed to get reasonable agreement. A group of universities have also performed an experiment with ^{28}Si on ^{28}Si at NSC, and have seen the interference minimum which the normal coupled channels calculation does not fit (Figure 3). Different re-orientation strengths are required to fit the data.

We now turn to another aspect of perhaps the same underlying mechanism as manifested in one and two nuclear transfer mechanism. This is the so-called slope anomaly. It was reported earlier (1988) by the Daresbury group, Lilley [5] showed that the transfer probability Pt when plotted as a function of the distance of closest approach showed deviation from the predictions of the semiclassical model, for one-nuclear transfer

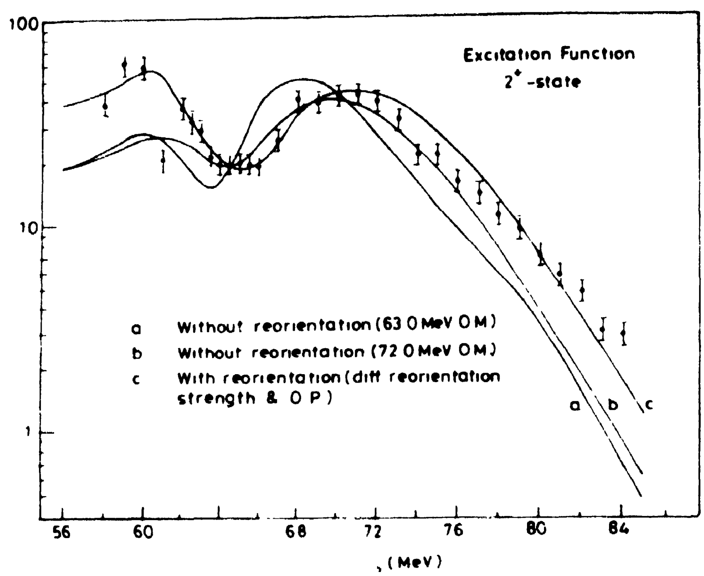

Figure 3. Inelastic scattering cross section as a function of energy

reactions. In the semiclassical model, Pt, is the integral of the transfer matrix element along a Rutherford trajectory. It is given by

$$P_t = N.\ \exp\,(-\,2\,\alpha d)$$

when d = distance of closest approach = $\dfrac{Z_1 Z_2 e^2}{2E}$ $(1 + \mathrm{cosec}\ \theta / 2)$

and $\alpha =$

where E_B = binding energy of the nucleon in the nucleus.

The results showed that at low energies (*i.e.* high values of *d*) for ^{58}Ni + ^{154}Sm, the semiclassical prediction did not agree with the measured data. Recently, a work from .Stonybrook Stonybrook by J F Liang *et al* [6] has reported measurements on ^{32}S + ^{92,98,100}Mo at energies of 109 MeV to 125 MeV. Here the two proton transfer probability deviates from the predictions of the semiclassical model.

The last item that I would like to touch upon, is the two nucleon transfer. Whereas the single nucleon transfer gives information on the single particle structure, the two nucleon transfer tells us about the pairing correlations. Two nucleon transfer could be either sequential or in cluster. For successive transfer, the overall transfer probability is the product of individual transfer probabilities. But for strong pairing correlations, two nucleon cluster transfer amplitude may be enhanced. If the configuration space is enlarged, the sequential transfer amplitude may eventually reduce due to contributions of alternating sign from consecutive shells. Paired transfer dominates in such cases. The enhancement of the two nuclear transfer cross section, is a measure of the collectivity, analogous to the enhancement of transition probabilities for the quadrupole vibration (0^+–2^+, two phonon) over the single particle estimate. Indeed, this thing is called a pairing vibration. Enhancement factors, can be as large as 100–1000. Nuclear deformation also plays a role by increasing the number of pairs coupled to non-zero angular momenta relative to the *S*-pairs. Pair transfer between collective states of heavily deformed nuclei show some interesting features. Oscillations are seen in the cross section angular distribution of ^{162}Dy (^{116}Sn, ^{118}Sn), ^{E}Lab = 637 MeV [7] for coupled pairs to high spins of 2.4.

In summary, interesting features are observed in quasi-elastic reactions. The heavy-ion transfer reaction throws light on the underlying reaction mechanism and research is still being vigorously pursued in this general area. There are other contributions in this conference that will leave testimony to my contention. With the advent of sophisticated techniques, such as recoil mass separator and 4π-gamma counters coupled with particle detectors to enable separation of states, the field in likely to yield further new information.

References

[1] J S Lilley, B R Fulton, M A Nagarajan, I J Thompson and D W Banes *Physics Lett* **B151** 181 (1985)

[2] M A Nagarajan, C Mahaux and G R Satchler *Phys Rev Lett* **54** 1136 (1985)

[3] G R Satchler *Nucl Phys*. **A472** 591 (1987)

[4] E M Takagui, G R Satchler, H Takai, K Koide and O Dietzsch *Nucl Phys* **A514** 120 (1990)

[5] J S Lilley *Direct Nuclear Reaction, Proc of International Seminar Indian Acad Sci*, *Bangalore* (1989)

[6] J F Liang, L L Lee, (Jr.) J C Mahon and R J Voltech *Pre Print*

[7] S Landowne, C Price and H Esbensen *Nucl Phys* **A484** 98 (1988)